16.2 A Programmable MEMS FSK Transmitter

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FSK modulation has been widely used in digital communication systems for applications as varied as remote keyless entry, telemetry, tire pressure monitoring systems (TPMS) and wireless sensor networks. Currently, most FSK modulation is achieved by loading a quartz crystal or a SAW resonator in an oscillator circuit with a switching capacitor, which is controlled by digital inputs, to change the oscillator frequency. However, this approach has limited frequency deviation and requires off-chip components for the frequency reference and modulation loading. Micromechanical resonators, on the other hand, have a natural frequency dependence of the polarization voltage [1] and have been used for low phase noise reference oscillators [2]. The MEMS FSK transmitter described in this paper accomplishes binary frequency-shifting of the MEMS synthesizer by switching between 2 polarization voltages of the resonator. In addition to the size reduction that the MEMS resonator enabled, the overall performance of the transmitter is as good as or better than current FSK transmitters on the market.

The micromechanical resonator used for the FSK transmitter is shown in Figure 16.2.1. It is fabricated with a 1.0µm double-poly single-metal micromachining process. The resonator structure consists of a beam with 6 release holes, 4 support beams, and a drive electrode placed 800Å underneath the resonator for electrostatic transduction. The location and dimensions of the release holes and the support beams are optimized so the quality factor (Q) of the resonator remains high (>6,000). The polarization voltage (V_P) and an AC excitation voltage are superimposed and applied to the drive electrode to excite the resonator beam at its natural resonant frequency. The resonant frequency f can be expressed as:

$$f = \sqrt{\frac{k_m - k_e}{m}} = \sqrt{\frac{k_m - (V_P^2 \varepsilon_0 A / d_0^3)}{m}} \qquad (1)$$

where k_m and m are the mechanical spring constant and mass of the resonator, respectively; k_e is the electric spring constant that is related to the interaction of the electric field between the resonator and the drive electrode and the resonator movement; A is the electrode area, and d_0 is the air gap between the electrode and the resonator. Based on this equation, the resonant frequency is a function of V_P. Therefore, by switching V_P between 2 voltages V_{P1} and V_{P2}, the resonator switches between 2 frequencies.

The system block diagram of the MEMS FSK transmitter is shown in Figure 16.2.2. As shown, a MEMS resonator is connected to an IC via pins RES1 and RES2. The 0.35µm CMOS IC has been specifically designed for use with the MEMS resonator. The reference oscillator accommodates the larger motional resistance and smaller phase shifts seen in MEMS resonators over the temperature range and over all process corner conditions. A similar design to that used in this IC was presented in [2]. The output frequency of the reference oscillator is then fed into a fractional-N synthesizer. The main loop for the fractional-N synthesizer consists of a charge pump, phase-frequency detector, on-chip loop filter, wideband VCO, and programmable divider. The programmable divider is modulated by the ΔΣ block. The digital control, programming and temperature compensation are all monitored by the control block. Functionality and communication are achieved through four pins: Enable, VDD, GND, and Output. The Enable pin shuts down all internal functionality except for memory. Once the synthesizer is programmed to a desired frequency, for example 433.92MHz, the digital modulation input signal is applied to the drive electrode of the resonator while the resonator beam is grounded.

The device modulation was measured by supplying an external bias plus a modulation signal. For initial measurements, the device was modulated with a simple square wave to prove the concept. By applying a 2.1V DC bias V_{P1} and a 0.9V peak-to-peak square wave V_{P2} superimposed on the bias (total peak voltage only 3.0V), a 150kHz frequency deviation was demonstrated as shown in Figure 16.2.3. This is 6× better than the deviation typically achieved with quartz crystal based FSK modulator (TDK 5110) and slightly better than a typical SAW-based device.

To evaluate the feasibility of using such a device in a real application, the device was biased to transmit at 433.92MHz with a frequency deviation of 80kHz and a modulation data rate of 20kb/s. It was then fitted with a compact antenna to transmit the modulated signal. The signal was received with both a spectrum analyzer to measure the spectrum as shown in Figure 16.2.4 and also with a commercially available receiver demonstration board (ADF7020). The receiver was able to demodulate the signal cleanly up to at least 20kb/s 10m away from the transmitter.

The –20ppm/°C linear temperature dependence of the MEMS resonator is electronically compensated. Figure 16.2.5 shows a total of +5 to –3ppm frequency deviation of a 433.92MHz oscillator from –40 to +85°C. The initial programmed frequency accuracy is less than 1ppm. Calibration information is stored on the IC using an internal ROM. The overall temperature coefficient exceeds quartz-based FSK transmitters by at least an order of magnitude and SAW-based transmitters by several orders of magnitude.

The measured data for the IC when used as a simple 433.92MHz frequency generator are shown in Figure 16.2.6. This IC can be programmed from 2MHz to 437MHz with 1ppm frequency accuracy. A 315MHz FSK transmitter has also been demonstrated with similar performance to show this system can be used for bands defined by customers. It is also important to note that the current consumption is high compared to other chipsets for similar applications because this IC is optimized to operate over a wide range of frequencies. If 315MHz and 433.92MHz are the focus, current consumption of the IC could be 10mA according to our simulations. Figure 16.2.7 shows the picture of a MEMS resonator and an IC on a PCB for FSK measurement, while the inset shows the BGA packaging of the final product.

With the size of 2.5×2.0×0.65mm^3, without the need for external resonator components, and with great transmission performance over temperature, the programmable MEMS FSK transmitter presented in this paper fits perfectly into applications of miniaturized, integrated, low-power communication systems. Moreover, for some wireless applications where MEMS is already part of the system, such as TPMS, MEMS resonators can be smartly fit into the manufacturing process of other MEMS devices such as pressure sensors, accelerometers and gyroscopes to achieve further cost reduction and system integration.

Acknowledgment:
Part of this work is supported by NIST ATP program grant 70NANB4H3001. The authors express special thanks to SWS Inc., Mike Simoneau, Jim Judkins, John Clark and Minfan Pai.

References:
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[2] W. -T. Hsu et al., "Low Phase-Noise 70MHz Micromechanical Oscillators," *Intl. Microwave Symp.*, pp. 1927-1930, June, 2004.

 1-4244-0079-1/06/$20.00 ©2006 IEEE

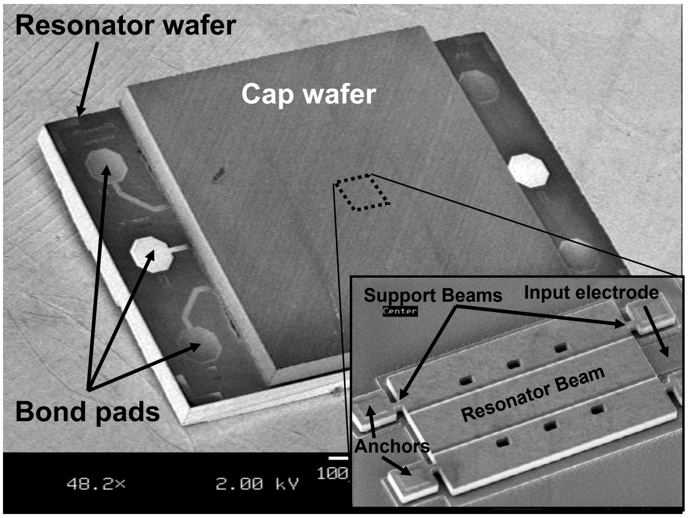

Figure 16.2.1: SEM photograph of a packaged resonator. The insetshows a micromechanical resonator structure inside.

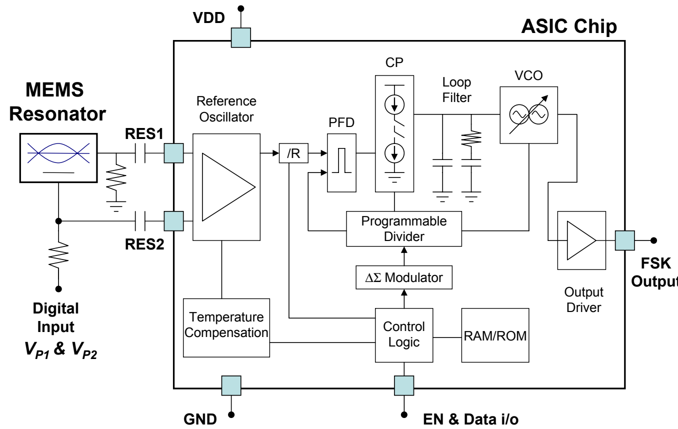

Figure 16.2.2: System block diagram of a MEMS FSK modulator.

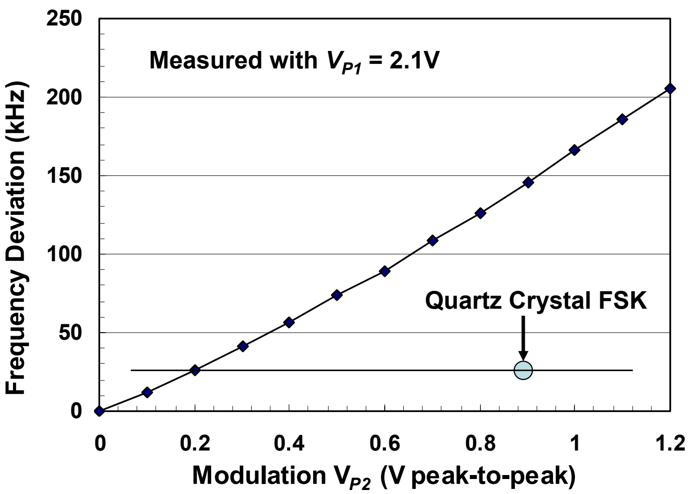

Figure 16.2.3: Frequency deviation versus modulation signal V_{P2} with constant *DC* bias voltage V_{P1}.

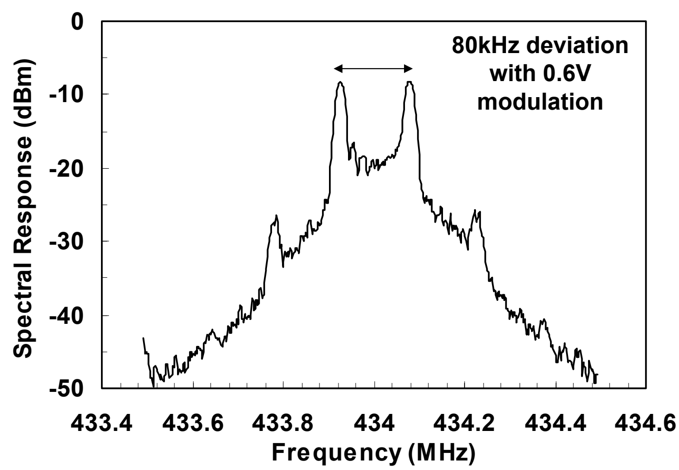

Figure 16.2.4: Output frequency spectrum of MEMS FSK at data rate 20kb/s.

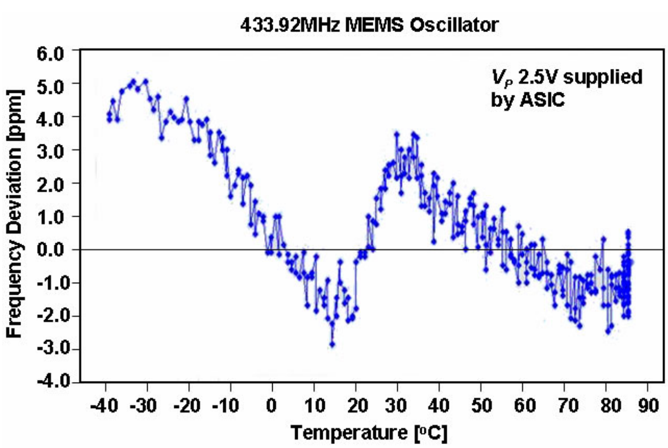

Figure 16.2.5: Measured total frequency deviation in ppm versus temperature of a 433.92MHz oscillator.

Parameters	Value
Output Frequency @ 3V, 25°C	433.9200MHz
Operating Supply Voltage	3.0
Operating temperature range	-40°C to +85°C
Current consumption (3V) with 15pF load	31.1mA
Stand-by current at +25°C	<1µA
Rise time Vddx0.1/Vddx0.9 at +25°C	0.7ns
RMS period jitter	5.5ps
FSK Modulation Voltage (on top of 2.1V)	0.6V/0.9
FSK Modulated Frequency Deviation	80kHz/150kHz

Figure 16.2.6: Summary of testing results.

Continued on Page 654

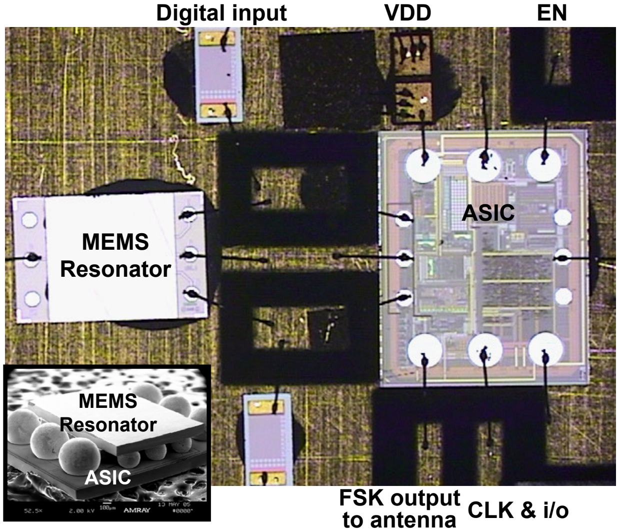

Figure 16.2.7: Photo of a MEMS resonator and an ASIC on PCB for FSK transmission.